Science Engineering Technology at AWE

# Discovery24

September 2013

This issue:

# Orion

## Shaping the future of plasma physics

### 2003

**December**
Initial design and costed proposal bid submitted to MOD.

### 2005

**April**
Proposal ratified by MOD giving 'authority to proceed'. Progress design for vendor and contractor for build appointed.

### 2006

**February**
Ceremonial ground breaking.

**June**
First piles.

**November**
Ground slab complete.

### 2007

**May**
Steel work skeleton erected.

**September**
Target Hall roof poured and building watertight.

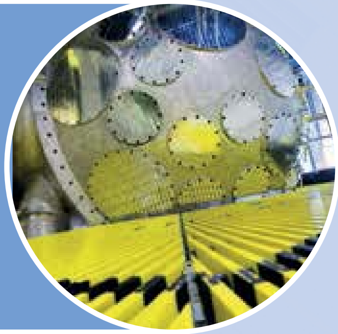
**December**
Electrical distribution system installed and main air handling units working.

### 2008

**May**
First Capacitor Bank Module arrived.

**October**
Compressor gratings delivered.

**December**
Target Chamber installed.

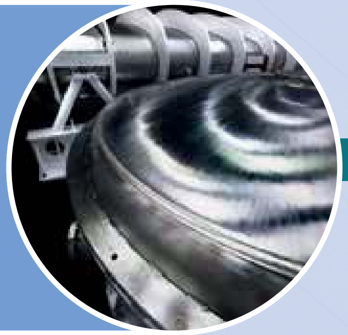


### 2009

**February**
Short pulse laser source operating.

**May**
Capacitor Bank Modules installed.

**July**
Compressor chambers installed.



### 2010

**September**
Long pulse and short pulse laser energy in Laser Hall.

**November**
First light on target.

**December**
One long pulse and one short pulse beam demonstrated to target.

### 2011

**July**
All beams fired up to required power in the Laser Hall. Achieved Full Target Chamber vacuum requirements.

**December**
All beams fired to target, demonstrating successful synchronisation of beams to required tolerance.

### 2012

**March**
First petawatt shot fired on target.

**September**
First academic proposals approved.

**December**
Aluminium foil compressed to twice-solid density and heated to over 5 million degrees.

### 2013

**Orion delivers major sub-strategic milestone supporting warhead certification.**

# Discovery 24

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Cover image:
Orion Target Chamber

**It gives me great pleasure to welcome you to the 24th edition of Discovery. This is a special edition focussed on laser plasma physics, and has been produced at a very exciting time for the field. Here at AWE the Orion laser facility has achieved operational status. A packed scientific programme on Orion for 2013 will include two open access academic campaigns. Internationally, the National Ignition Facility (NIF) in the US has produced interesting results in experiments towards sustained fusion, while the HiPER and LIFE programmes for future fusion energy production are now mature and ready to progress.**

In my role as Head of Plasma Physics, I am particularly proud that the Orion laser facility here at AWE has achieved its final commissioning milestone. AWE has worked in the field of laser plasma physics for over forty years and Orion represents one of the largest capital science investments ever in the UK. Several of the articles herein describe the laser, its development and its importance to AWE programmes for example in the provision of material properties data at extreme conditions of temperature and pressure. The system has now demonstrated a unique capability to heat aluminium to over 5 million degrees at more than twice solid density. These high energy density physics experiments are performed to support AWE's warhead certification programme. The data are also pertinent to conditions in the cores of large planets and stellar interiors which are of interest to the wider academic community.

Orion is attracting significant interest from our international collaborators and UK academia. From 2013, the facility will be available for use by the UK academic community for up to 15% of the available time. A number of submissions were received, and managed through the Central Laser Facility STFC Rutherford Appleton Laboratory (RAL) access panel. We are confident that this represents an excellent opportunity for AWE and the plasma physics community in carrying out novel experiments of importance to science in the UK.

Although AWE does not directly contribute to fusion energy programmes, AWE does share existing capabilities in target design and manufacture to aid fusion energy programmes such as HiPER, with the aspiration to delivery clean, carbon zero, energy in the future.

Orion became fully operational in April 2013 and there are exciting times ahead. I hope you enjoy the articles in this special edition of Discovery and that you feel the same sense of pride as I do in the fantastic capabilities for plasma physics here at AWE.

**Professor Andrew Randewich**
**Head of Plasma Physics**

# History of High Power Lasers at AWE

A nuclear reaction generates extreme conditions; temperatures reach millions of degrees Celsius, with pressures exceeding millions of atmospheres. Under such conditions, electrons are stripped from atoms, materials turn into plasmas, and we enter the realm of plasma physics. In order to generate such conditions in the laboratory, enormous energy densities are required to turn material from the solid state into the plasma state.

In the mid 1970's the Ministry of Defence decided that there was a requirement to investigate the possible uses of high power laser systems for both weapons work and inertial fusion energy experiments. Some work on the use of high power $CO_2$ lasers had already been going for some time, but following the successful development of solid state Neodymium-glass lasers such as ARGUS and SHIVA at Lawrence Livermore Laboratory (LLNL) in the US, the decision was made to start a laser capability at AWRE.

A small laser system called MERLIN operating at the AWRE outstation at Foulness was relocated to the Aldermaston site in the late 1970's to help develop an in house knowledge base of how to design, operate and use lasers for plasma physics experiments. At the same time the requirements for a larger system then called AFL-1 (Aldermaston Fusion Laser -1), with around a Terrawatt of power was developed. These requirements were translated into what became the HELEN laser system.

The HELEN laser, based on the technology developed for the SHIVA laser at LLNL, comprised two opposing infra red laser beams, 200 mm in diameter, each delivering around 100 J in 100 ps. The facility was opened by Her Majesty The Queen in 1979 and started delivering experimental data in support of the design physics community.

Both the MERLIN and HELEN facilities operated through the 1980s each receiving a number of upgrades in both energy and operating wavelength; HELEN was converted to operate in the green region (527 nm) while MERLIN did some experiments in the ultra violet region (351 nm). In the late 1980's HELEN received a further upgrade adding a third smaller backlighter beam. HELEN operated in this configuration for just over 10 years fielding some unique, world leading experiments and developing and implementing advanced laser and diagnostic technologies. At the same time, the requirements for operating the MERLIN facility were reduced and it was closed in the early 1990's.

In late 1990's advances in laser design in the U.S provided a route for HELEN to be reconfigured to provide a more robust, capable and compact facility. This rebuild to a multipass configuration was possible due to the provision of additional amplifier assemblies from LLNL.

In 2004 HELEN's backlighter beam was converted to provide a short pulse chirped pulse amplification capability. This capability was based on a similar design implemented at the VULCAN laser facility at Rutherford Appleton laboratory in Oxford. HELEN operated very successfully for more than 5 years in this configuration and provided a unique capability to deliver world class plasma physics experimental data. In 2009 HELEN was closed down to enable staff to move to Orion.

Orion succeeds HELEN and allows AWE to generate high energy density plasmas. A major area for study is the state of different materials and how they interact under great heat and pressure. The state of a particular material can be described by its equation-of-state (EOS); this relates the density of a material to the temperature and the pressure it is experiencing. Another phenomenon to be explored on Orion will be how heat and energy flows under such conditions; this provides an understanding of opacity in the plasma state.

This edition of Discovery provides an overview of the Orion laser system, facilities and possible areas of research that could be explored using Orion.

# The Orion Laser System

## Design and Performance

**This article describes the design and performance of the ten long pulse and two short pulse beam lines of the Orion facility.**

Each long pulse beam has a nominal operating specification of 500 J in a 1 ns square pulse at a wavelength of 351 nm (in the near-ultraviolet region of the spectrum). This pulse can be focussed onto a target in a spot less than 100 $\mu$m across, resulting in a focussed intensity per beam of the order $10^{16}$ Wcm$^{-2}$.

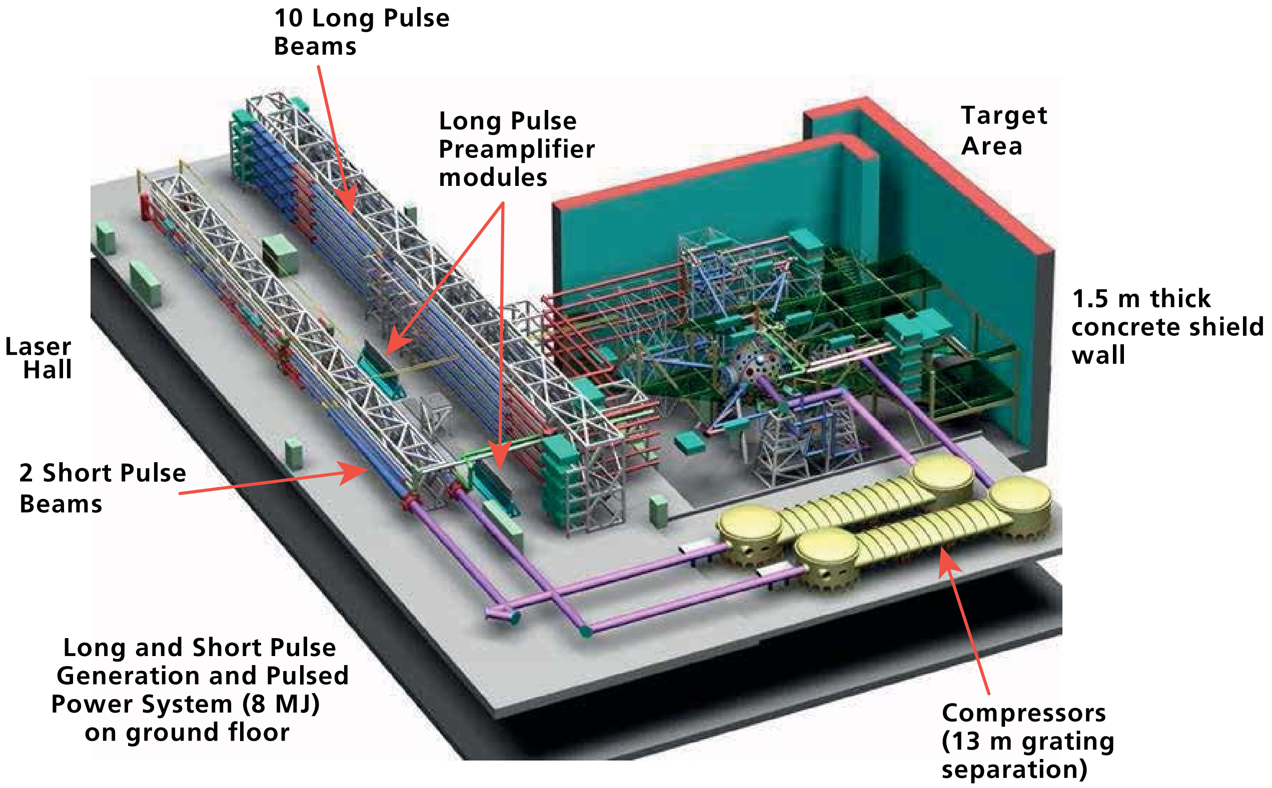
The short pulse beams each deliver 500 J at 1053 nm in a pulse of duration 500 fs. An adaptive optics system enables focussing close to the diffraction limit. The resulting focussed intensity is of the order $10^{21}$ Wcm$^{-2}$ and the peak power is 1 petawatt in each beam line.

This makes Orion a world-class facility for the study of high energy density physics. In this article an overview of the design of the various beam lines is presented, along with some of the system performance data that underpin the system commissioning.

## Facility Layout and Overview

Figure 1 shows the layout of the Orion lasers. The long pulse beams consist of two stacks of five beam lines, supported on each side of a large space frame structure. Each stack is seeded with a pre-amplifier module (PAM), which amplifies pulses up to the 200 mJ level and spatially shapes the beam. The PAMs themselves are seeded with pulses of energy roughly 50 pJ, using a pulse generation system housed beneath the laser hall, known as Optical Pulse Generation 1 (OPG1). The long pulse beam line

**FIGURE 1**



Orion facility layout.

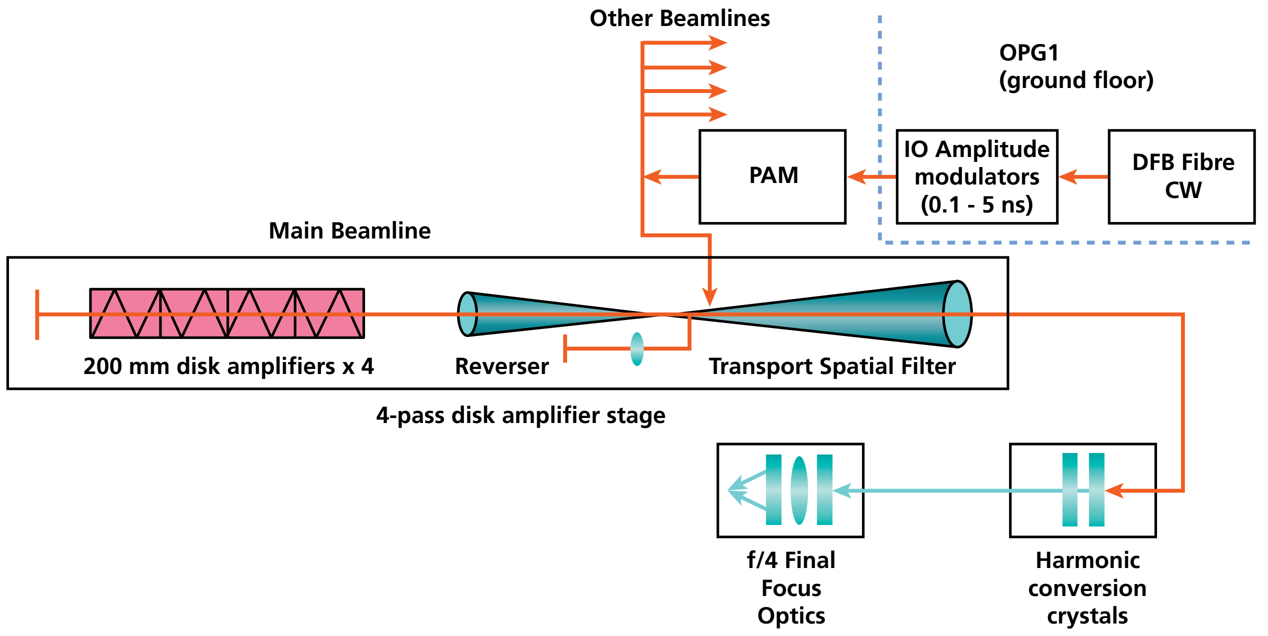
> “At this point the pulse has power in excess of 1 petawatt, it has the characteristics of a flat sheet of light, 600 mm across and only 1/7th of a millimeter thick.“

architecture comprises four 200 mm aperture disk amplifiers, which are four-passed using angular multiplexing. The output at the fundamental wavelength is about 750 J, with a beam diameter of 300 mm, which is then frequency tripled in the target hall, yielding 500 J per beam.

The short pulse beam line components are supported on a second space frame, one beam line per side. These are seeded with pre-amplified pulses from Optical Pulse Generator 2 (OPG2), a room below the laser hall which produces roughly 50 mJ pulses. These are amplified in a rod amplifier system and multiple disk amplifiers at increasing aperture to about 700 J in total. The pulses emerging from OPG2 are chirped, namely the wavelength of the pulse sweeps from longer values at the leading edge of the pulse to shorter at the trailing edge. The amplified output of the beam line is expanded to 600 mm diameter and then directed into a compressor system, which lays the constituent wavelengths back on top of one another in time, thus recovering a pulse with as short a duration as possible, commensurate with its bandwidth, see Box 1.

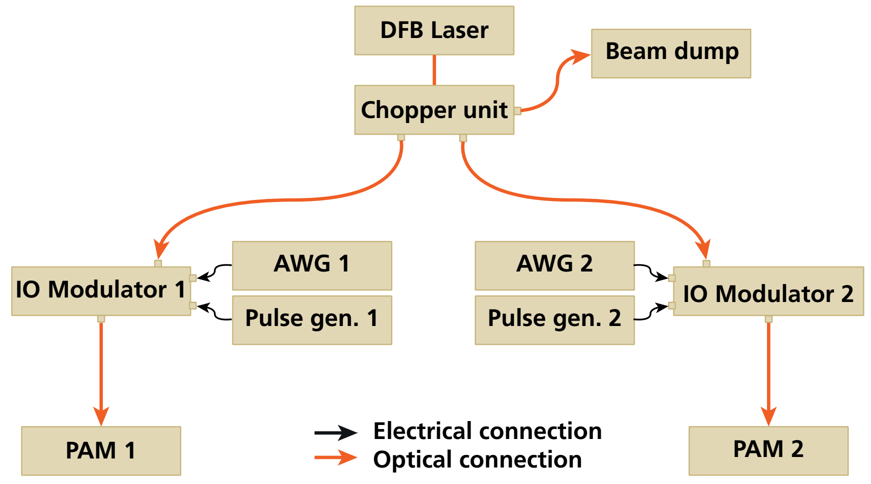
At this point the pulse has power in excess of 1 petawatt, it has the characteristics of a flat sheet of light, 600 mm across and only 1/7th of a millimeter thick. Its intensity is too great to pass through any dielectric medium. Therefore, since the target interaction takes place under vacuum, the compressors, beam transport and target chamber must form a single, large vacuum system. Finally, the beam is focussed to target using a paraboloidal mirror, since it is too intense to pass through a lens.

**FIGURE 2**



Long pulse beam line schematic.

**FIGURE 3**



Optical Pulse Generation 1 system schematic.

## Long Pulse Beam Line Design

A schematic of the long pulse beam line is shown in Figure 2. The original source of light is a commercial, distributed feedback (DFB) fibre laser delivering up to 1 W of CW power at 1053.0 nm. This beam is chopped into a 1 kHz chain of 400 ns pulses using an in-fibre acousto-optic modulator and then split between two outputs. The two chains of pulses are sent to the two, independent, integrated-optic (IO) modulators. These modulators sculpt the 0.1-5 ns shaped pulses and are each driven by an arbitrary waveform generator (AWG), plus a square pulse generator to sharpen the rise/fall time to less than 100 ps.

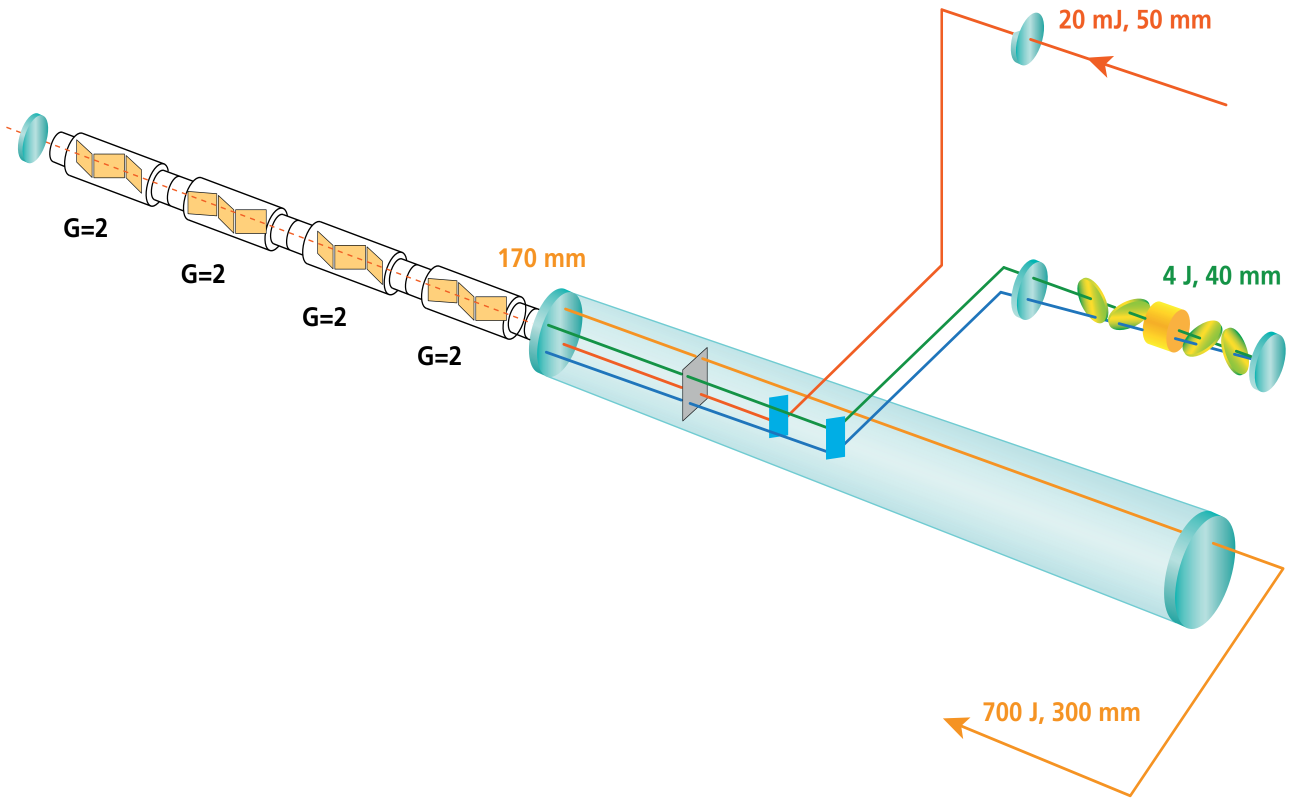
When the two-way split and the inherent system losses are accounted for, the output of the system is roughly 50 mW e.g. 50 pJ for a 1 ns square pulse. This is more than adequate to ensure good signal to noise ratio from the PAM.

An overview of OPG1 is shown in Figure 3. The shaped pulses are sent to the PAMs along two long transport fibres. The system is entirely fibre coupled which minimises maintenance/realignment and makes it inherently safer than an equivalent free space system.

The PAMs house a regenerative amplifier, based on a flash lamp pumped Nd:YLF rod, a spatial shaping stage, a 2D smoothing by spectral dispersion (2D-SSD) system based on bulk phase

> “The rod amplifier system engineers four passes of the rod using polarization switching with a quarter waveplate.”

**FIGURE 4**



**Overview of Transport Spatial Filter and the disk amplifiers.**

modulators, a four-passed 32 mm aperture rod amplifier and a diagnostics package. These systems are mounted on both sides of a vertically mounted optical table with dimensions 5.5 m by 1.5 m.

The regenerative amplifier utilizes roughly 50 passes through a self-imaged ring cavity to amplify the OPG1 pulses to a few millijoules. The beam shaping consists of over filling a serrated aperture. The residual dome from the Gaussian beam is used to compensate the slight radial gain non-uniformity in the 32 mm aperture rod amplifier.

The SSD system uses phase modulators at 2.45 GHz, and 10.4 GHz to impart spectral sidebands on the beam, which are dispersed in orthogonal directions using diffraction gratings. Used in conjunction with phase plates, just prior to final focussing, this system can smooth out the laser speckle seen in the focal plane.

The rod amplifier system engineers four passes of the rod using polarization switching with a quarter waveplate. A permanent magnet Faraday rotator (FR7) switches the beam in and out of the rod amplifier system. The rod amplifier system is angularly multiplexed so that the on-axis path can be blocked at the focal plane of its relay telescopes, so as to inhibit laser oscillation.

> “The regenerative amplifier utilizes roughly 50 passes through a self-imaged ring cavity to amplify the OPG1 pulses to a few millijoules.”

Although each PAM is capable of delivering multiple Joules, in the current system design they are only required to yield up to 200 mJ. The output from each PAM is split either five or ten ways (there is an option to seed either all ten beam lines with a single front-end, or have independent seeding of each stack of five beams lines).

Each long pulse beam line requires about 20 mJ of seed energy to achieve its required 750 J output at 1053 nm. The PAM output is split using polarizer -waveplate combinations and are image relayed into the long, transport spatial filter (TSF). The TSF is a telescope with a square array of four pinholes (roughly 5 mm in diameter) at its focal plane. The beams are injected near this position. Beyond focus, the beam expands in the TSF to 170 mm before injection into the four 200 mm aperture disk amplifiers. Figure 4 is an overview of the TSF and the disk amplifiers.

Each amplifier houses three glass slabs, doped with neodymium, and delivers a small-signal gain of up to 2.4. In practice the gain used is about 2.1, so as to control the potential for parasitic lasing in the cavity. The beam is angularly multiplexed such that different passes of the amplifiers can be spatially separated near the pinhole plane of the TSF.

After two passes of the four amplifiers, the beam re-enters the TSF and is directed, near the pinhole plane, into a reverser system, where it is re-collimated at 40 mm diameter and returned to the TSF. At this point, the energy is about 4 J.

The reverser also houses Pockels cells to isolate the gain from passes 1 and 2 and passes 3 and 4. Two more passes of the disk amplifiers brings the energy to about 750 J. This time it passes straight through the TSF, being expanded to 300 mm, and is directed into the target hall.

Frequency tripling is effected by a pair of crystals. The first is a type I doubler with thickness of 14 mm to achieve the optimal 2:1 energy ratio of doubled and fundamental light at the nominal operating point. The second is a type II mixing crystal, of 12 mm thickness. The result is a third harmonic beam with a polarization the same as the input fundamental beam.

Five dichroic transport mirrors each discriminate between residual wavelengths and the $3\omega$ beam with an efficiency of ~100:1, giving a very pure $3\omega$ beam at the target. Their geometry is such that the beams are orientated onto target in two opposing cones of five beams. The beam lines themselves do not oppose each other through the target chamber; the two cones of beams are mirror images of each other about the target plane i.e. a plane at the apex of each cone, orthogonal to their mutual axis.

The axis of each individual beam is also rotated by the geometry of the transport mirrors such that the polarization of each beam is in the ‘p’ state, relative to the target plane, to better couple laser radiation into a typical target plasma. Final focusing of the beams is achieved using the long pulse final optics assembly (LPFOA) which consists of an optional kinoform phase plate, a vacuum window, a 1.2 m focal length lens and a debris shield.

## Short Pulse Beam Line Design

Figure 5 is an overview of the short pulse beam line. The short pulses are generated by a commercial Titanium-Sapphire oscillator delivering pulses with a bandwidth of about 12 nm around 1054 nm. Immediately these pulses are split to seed each of the two short pulse beam lines. A common oscillator is used to realise the best timing jitter between the two short pulse beams. On each side of the split, the pulses are sent to two independent Offner triplet stretcher systems.

These are four-passed systems with an effective grating separation of 3.25 m per pass, with a 1480 mm$^{-1}$ diffraction grating at 47.9° angle of incidence. This compensates the compressor with a 13 m grating separation and the same grating specification.

Two independent stretchers are used so that each short pulse beam can operate with a different pulse duration, specified to be between 0.5 and 20 ps. The resultant chirp is 300 psnm$^{-1}$. The stretcher imparts a hard spectral clip at 18 nm, so the stretched pulse duration is 6 ns; there is significant power (about 20% of peak) at these pulse extremities.

The first stage of amplification also takes place within the OPG2 subsystem. An optical parametric chirped pulse amplifier (OPCPA) is used to conserve pulse bandwidth. OPCPA is a nonlinear optical technique in which a flow of energy can be effected from an intense "pump" pulse to a much weaker "signal" pulse. A third pulse, known as the "idler", is generated as a by-product and discarded.

This technique is used here principally because a large gain can be realized across a wide range of wavelengths. The bandwidth is maintained during the first gain stages to a much greater extent than is possible using laser amplification. The OPCPA system for both beam lines is pumped by a single, commercially sourced, pump laser. This is an Nd:YAG system operating at the second harmonic, which was specified to have very flat pulses both spatially and temporally. The pump pulse is of 6 ns duration and so amplifies the full bandwidth from the stretcher. The amplification occurs in three stages, the final two of which exhibit strong pump depletion. The more intense regions of the pulse are driven to the point of back-conversion to achieve optimal output energy stability. In this regime, the signal pulse mimics the spatial and temporal properties of the pump pulse; it becomes a top-hat, square pulse.

"The short pulses are generated by a commercial Titanium-Sapphire oscillator delivering pulses with a bandwidth of about 12 nm around 1054 nm."

Each OPCPA stage can produce about 150 mJ, which is much greater than that required to meet the short pulse baseline performance, which results in greater operational flexibility.

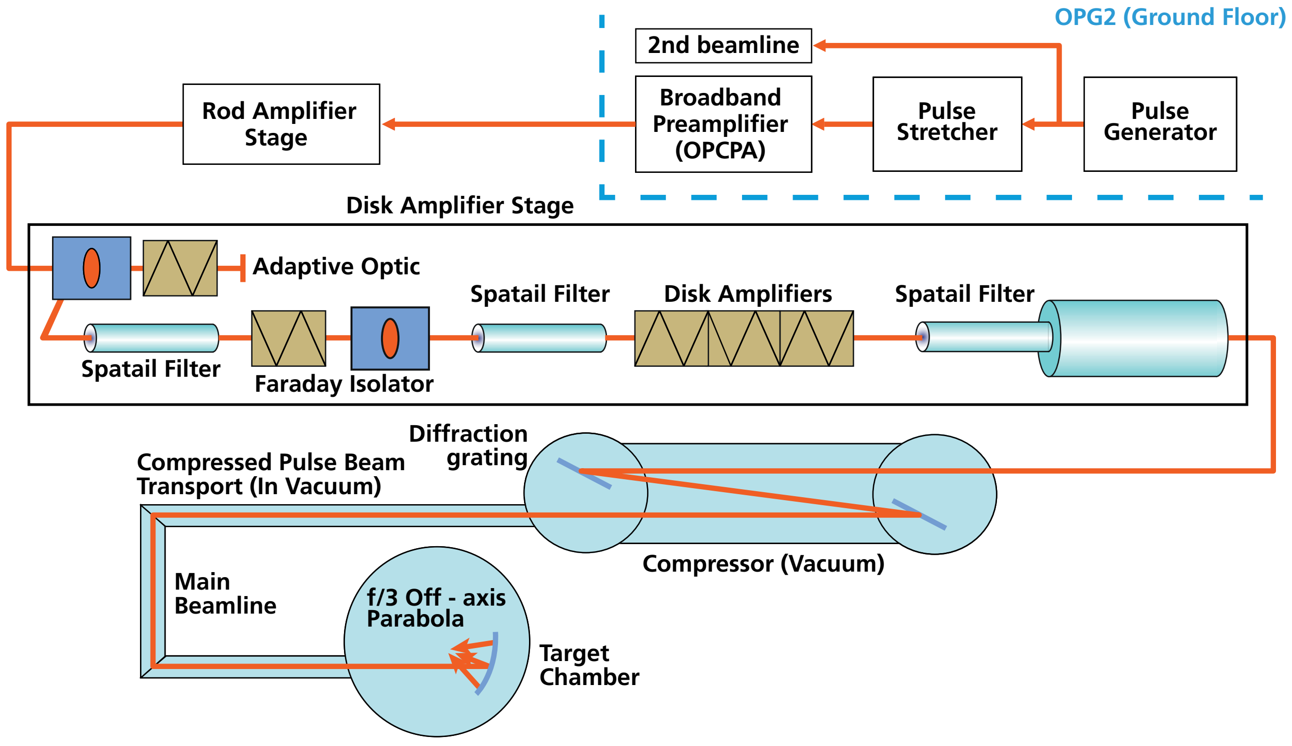
The OPCPA output is expanded and then apodized at 16 mm diameter such that only the cleanest, central region of the beam is injected into the main short pulse laser chain. This begins with a four-passed mixed glass, 32 mm aperture rod amplifier subsystem. This uses phosphate and silicate glass, which have offset gain spectra, in order to maintain as much bandwidth as possible before injection into the disk amplifiers.

Other than the use of two rods, the design is very similar to the rod amplifiers on the long pulse PAMs. This system produces about 2 J for baseline performance with 9 nm bandwidth.

The beam is then expanded to 86 mm diameter before it is injected into a 100 mm aperture Faraday rotator. This has two functions; it allows a double pass of the first disk amplifier and secondly it acts as an optical isolator for back-reflections. In the double passed disk amplifier the pulse experiences a small signal gain of about 6 per pass. This is somewhat lower than the gain for a monochromatic pulse.

The beam is then expanded to 140 mm diameter, where it passes through a 150 mm aperture disk amplifier, with a gain of about 4. The next component is another Faraday rotator, with the sole function of isolation against back reflections.

**FIGURE 5**



**Schematic of a short pulse beam line.**

The beam is then expanded to 180 mm and single passes three 200 mm amplifiers, of the same design as those on the long pulse beams. The beam line is shown schematically in Figure 5.

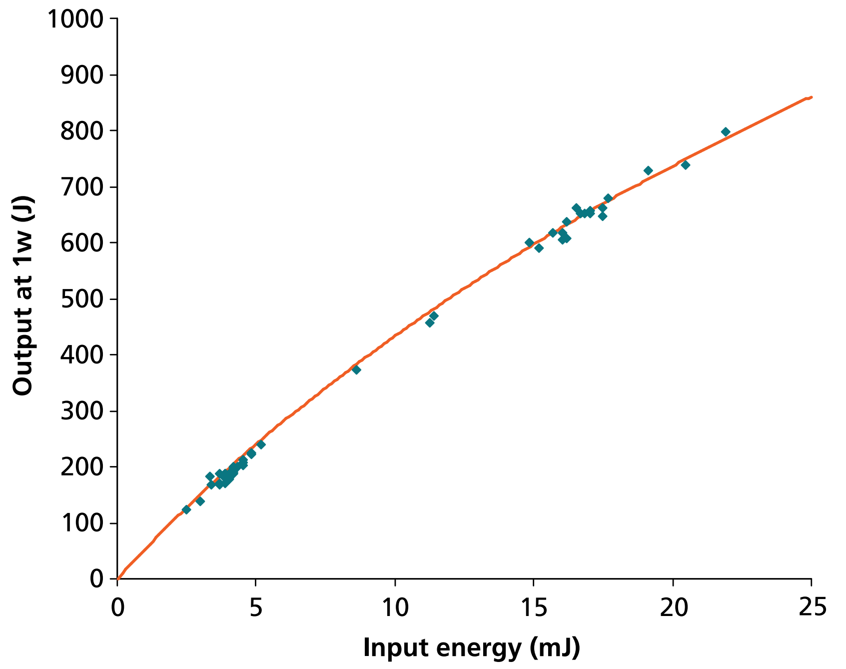
The result is pulses with about 700 J and 5 nm bandwith. These are expanded to 600 mm diameter and image-relayed into the compressor vacuum vessels, which contain single pass compressor systems, using the same grating configuration as the stretcher, and a 13 m grating separation. The gratings are gold-coated and have 940 mm aperture in the horizontal plane. There is a slight spectral truncation in the near-field on the second grating. Long vacuum transport systems send the beam from the compressor vessels to the target chamber, where they are focused with f/3 paraboloidal mirrors.

"In addition to these key beam parameters, the pulse energy through the laser chain must be well understood, if laser induced damage is not to be exhibited. "

## Long Pulse Beam Line Performance

The performance of all the beam lines are closely monitored using laser diagnostics at multiple locations along the laser chain. The principal locations for diagnosis are directly after the TSF output and after the

**FIGURE 6**



**Laser chain output energy (prior to frequency conversion) versus injected pulse energy for an example long pulse beam line.**

frequency conversion crystals. The former location monitors the spatial characteristics of the beam as it emerges from the TSF (the near-field) and also how well the beam can be focused (the far-field). Closely related to this is the wavefront error on the beam, which is measured using a Shack-Hartmann wavefront sensor.

The temporal profile of the pulse is measured using a streak camera at this point. After frequency conversion, the near- and far-field beam profiles are measured again, as is the temporal profile and the presence of any pre-pulses in advance of the main pulse is monitored using a pair of photodiodes.

In addition to these key beam parameters, the pulse energy through the laser chain must be well understood, if laser induced damage is not to be exhibited.

The plot in Figure 6 shows the energy produced by one of the long pulse beam lines as a function of the input pulse energy for a given capacitor bank voltage. The effect of gain saturation is visible in the lower gradient at higher energies. The curve is a simple gain saturation model fitted to the data.

This model is used during operations to determine the laser parameters required to achieve a requested energy and to ensure that the maximum is not exceeded with its attendant risk of laser-induced optic damage.

## Short Pulse Laser Performance

There are more properties of the laser pulse that are pertinent to laser performance and so an extended suite of laser diagnostics is required. In addition to the usual near- and far-field images, the spectrum of the pulse is important, as is the level of any pre-pulses present on the beam, post-compression. Since intensity is the principal parameter to be maximised, the requirements on the focal spot of the pulse are much tighter, requiring an active, adaptive optics system to be fielded and optimised. Finally, the duration of the pulse is much shorter than can be measured using conventional electronics and so optical techniques must be deployed to ascertain the pulse shape indirectly.

Immediately after the amplifiers a diagnostics station measures the beam profiles, the wavefront, the pulse energy and the pulse spectrum. This determines that the pulse has suitable characteristics for injection into the compressor system. The large compressor gratings are very expensive and difficult to replace. They are also the most vulnerable components to laser induced damage. Great care must be taken to ensure the suitability of the pulse prior to compression.

After the compressor, leakage through one of the turning mirrors is used to diagnose the pulse characteristics. As the pulse is short, the intensity can build up in the diagnostics package to levels such that nonlinear optical effects can perturb the beam quality and this must be managed carefully. The near-field profile is dispersed horizontally; this is a consequence of a pulse with significant bandwidth propagating through the compressor system.

The far-field is monitored to ensure that the compression process has not disrupted the wavefront of the beam. The pulse spectrum is also measured, as is the pulse duration. The pulse is of order 500 fs long, this is much too short to be measured directly using conventional techniques.

A device known as an autocorrelator was designed and built at AWE to make an estimate of the pulse duration. It splits the pulse in two halves, which are then made to shear across each other spatially in a nonlinear optical medium. This technique realises a temporal-to-spatial mapping so that the pulse duration can be inferred by imaging the output of the pulse's self-interaction on a camera. What is measured is not the pulse shape itself, but rather a quantity known as the intensity autocorrelation of the pulse.

Given certain assumptions about the nature of the pulse, an estimate of the pulse duration can be obtained. As this technique is necessarily indirect, other pulse duration diagnostics have been commercially obtained and fielded on the system to yield further information about the temporal behaviour of the pulse. These devices are also indirect, but operate on different principles, thus providing some reassurance that a reasonable estimate has been made.

A key parameter of interest to facility users is the pre-pulse contrast ratio of the short pulses. This is the ratio of the peak power of the pulse to the power at some defined time before the peak. Photodiodes with suitable attenuation were used to measure the pre-pulse contrast a few nanoseconds before the peak of the pulse. This was measured to be between $10^7$ and $10^8$ for ~3 ns prior to the peak. Although this meets the original specification, for some experiments it is desirable to improve upon this pre-pulse level.

A development programme is under way to improve the contrast from OPG2, but the facility is able to offer enhanced contrast using another technique. There is an option to frequency-double the output from one of the short pulse beams, post compression. Since the lower intensity pre-pulse will not double with high efficiency, the contrast of the doubled pulse is greatly enhanced.

An additional vacuum vessel is provided after one of the compressors to redirect the beam through a doubling crystal and on to the target chamber. The crystal thickness that is optimal for doubling such an intense pulse is around 3 mm.

The aperture of such a thin crystal is limited to 300 mm, so that the SP beam must be apodized to this diameter, thus losing about 70% of the incident energy. In addition a doubling efficiency of about 65% is achieved, leading to a maximum doubled energy of about 100 J. This capability enables novel opportunities for experiments that require high contrast or shorter wavelengths.

## Summary

The combination of long pulse beam lines with two independent short pulse systems gives the Orion facility great flexibility in the range of experiments that can be performed.

During 2011 and 2012, the laser was commissioned successfully to yield the advertised performance requirements and is now ready to operate as a fully capable user facility.

## BOX 1

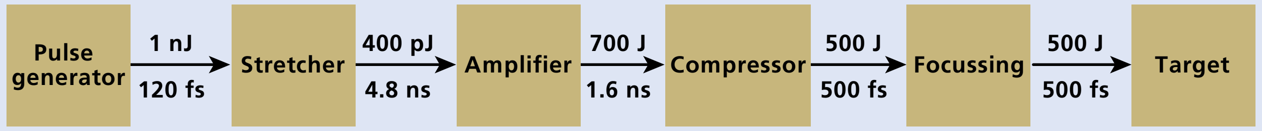
### Chirped Pulse Amplification

Ultra-short laser pulses are not difficult to produce at low energies. However amplification to any significant energy is difficult as the intensity is high. This drives non-linear effects in optical materials, disrupting the spatio-temporal profile of the pulse, leading to laser-induced damage. This could be avoided if the laser pulse could be lengthened prior to amplification and recompressed afterwards. This concept forms the basis of chirped pulse amplification (CPA). A generic CPA beam line consists of pulse generation, stretching, amplification and recompression. Focussing to a small spot size produces a high intensity pulse.

Any temporal waveform may be expressed as a superposition of single-frequency wave trains of the right amplitudes and phases. Adjusting the amplitudes and phases allows manipulation of the waveform. Adjustment of temporal profile can be seen in the stretcher and compressor of a CPA beam line as these devices apply distortions of spectral phase. It is important that these are controlled with high accuracy. Residual distortion must be minimised to allow good recompression of the pulse.

At the compressor pulse energies are high and a large aperture is needed to keep energy density below the threshold for laser-induced damage to the optical components. Compressors typically consist of one or more grating pairs, each arranged with the gratings face to face.

The beam size is much smaller and more manageable at the stretcher. The need to produce an identical but conjugate grating geometry demands the use of an optical imaging system. A virtual grating pair is produced with the gratings back to back.



**Functional block diagram of generic chirped pulse amplification beam line.**

## BOX 2

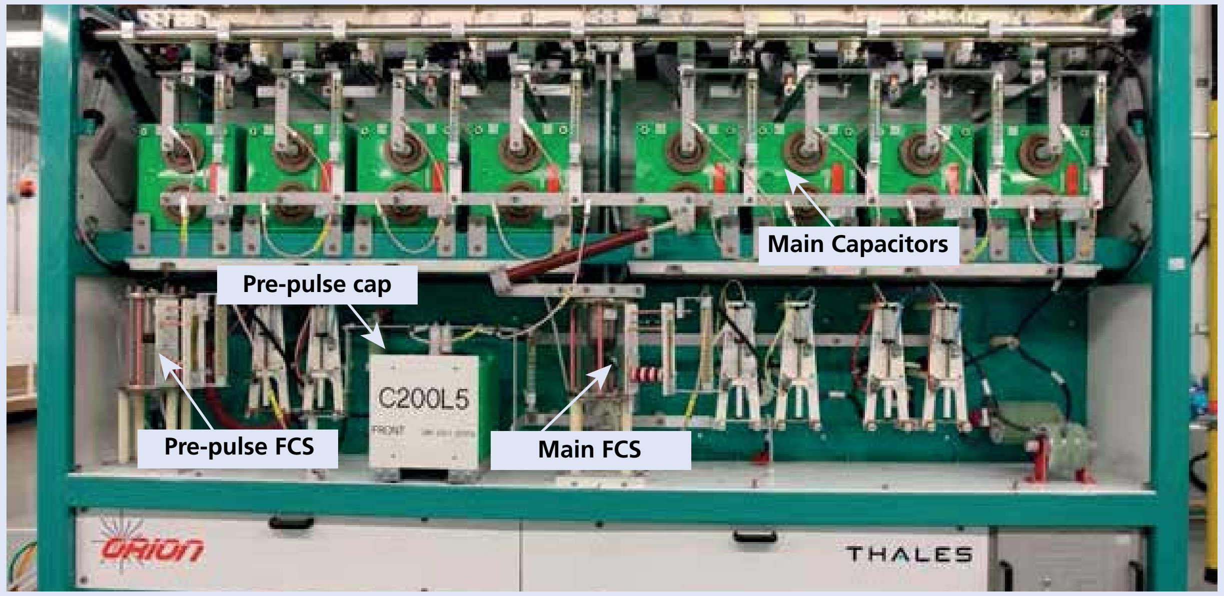
### Orion Pulse Power System

The Orion Pulsed Power System supplies 8 MJ of energy to drive the Orion Laser amplifiers and Faraday Rotators. The main pulsed power system consists of fourteen Capacitor Bank Modules (CBMs) which can be subdivided into ten banks driving 200 mm amplifiers on ten long pulse laser beams, two banks driving 200 mm amplifiers on two short pulse beam lines, one bank driving 100/150 mm amplifiers on the short pulse beam lines and a bank driving all the Faraday Rotators.

A CBM typically consists of two halves with each half-bank having eight 150 $\mu$F main pulse charge storage capacitors. The half-bank driving Laser Amplifiers have a 25 $\mu$F pre-pulse storage capacitor installed to allow the flashlamps to be pre-ionised. A single 25 kV power supply per half-bank, charges the main capacitors with both the front and rear pre-pulse capacitors charged by means of the front unit. The main capacitors in each half are switched by a single air pressurised fast closing spark gap switch (FCS) with the duty of switching both front and rear pre-pulse capacitors undertaken by a FCS mounted in the front half of the CBM. Each FCS is triggered by a 120 kV output Marx generator. The system is timed to switch the pre-pulse capacitors in the region of 300 $\mu$s prior to the main pulse with the main pulse then having a total duration 490 $\mu$s.

The two short-pulse beam lines have additional amplification in the form of 100 mm and 150 mm amplifiers which are driven by a single CBM operated as two independent halves. The CBM driving the Faraday Rotators consists of a half-bank and is configured to drive 100 mm and 150 mm Faraday Rotators.

The charging and firing of a half bank is managed by a built in Command and Control Module (CCM) which also monitors the banks output. All of the CBM internal control signals are communicated by compressed air or fibre optics to mitigate the effects of electromagnetic pulses and interference. The CCM communicates with an external Test Controller via fibre optic cables which controls and monitors the capacitor banks' operation. The Pulsed Power system is controlled in conjunction with the laser by means of commands sent to the Test Controller from the Main Laser Control Room.



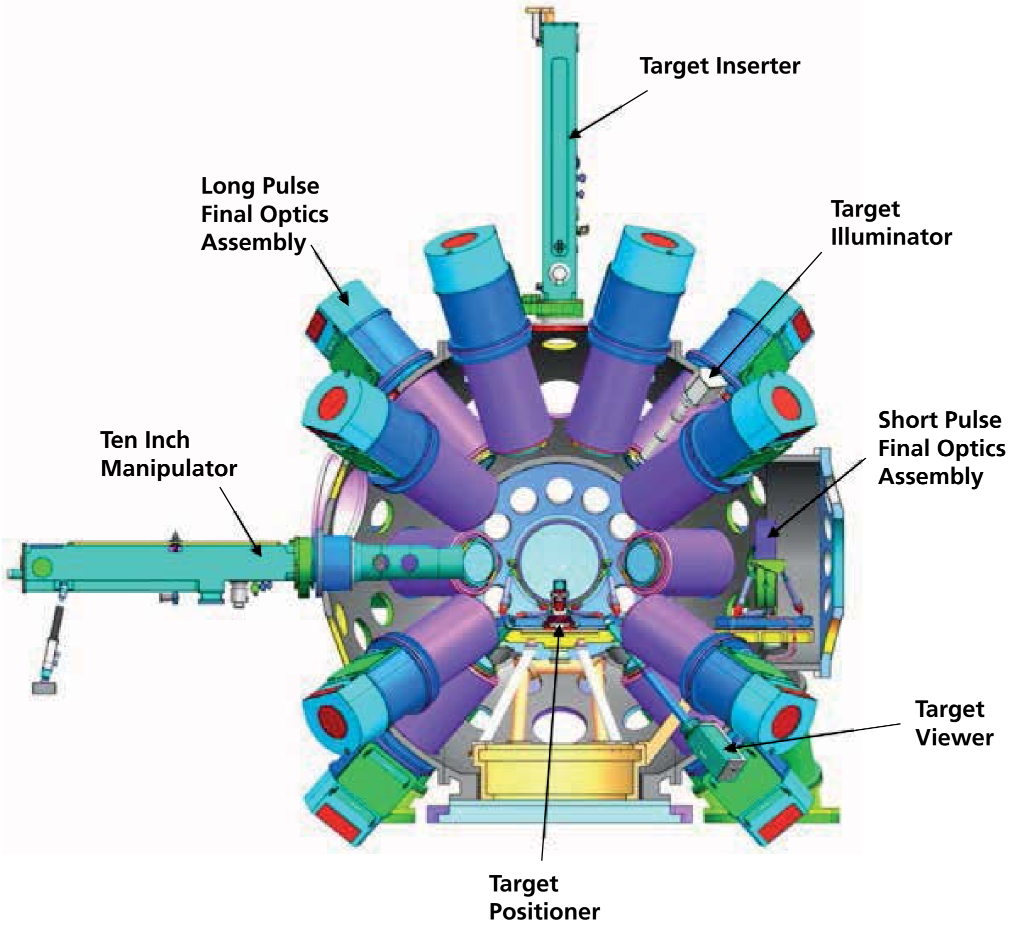
# Orion Target System

**The Orion target system comprises of six major sub-systems that must all work together. Figure 1 is a model image of these sub-systems. This article will provide technical information on the sub-systems and how they interact.**

The sub-systems that make up the Orion target system are:

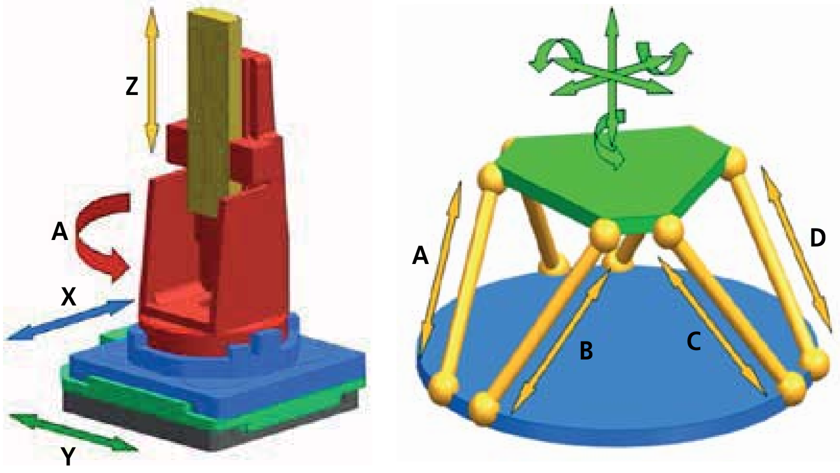
- Short Pulse Final Optics Assemblies (SPFOAs) –The final focussing parabolic mirrors in the short pulse beam lines
- Long Pulse Final Optics Assemblies (LPFOAs) – The last few optical components in the long pulse beam lines
- Target Positioning System (TPS) – The manipulator used to position and orient the target into the required position within the target chamber
- Target Inserter (TI) – The device used to insert the experimental target into the target chamber
- Ten Inch Manipulator (TIM) – Inserts and positions removable diagnostics into the target chamber
- Target Viewer and Illuminator System (TVS) – Provides remote camera views of the target

**FIGURE 1**



Model of Orion target system showing major sub-systems.

**FIGURE 2**



(a) (b)

Examples of manipulators a) Serial Stacked slide mechanism b) Parallel hexapod mechanism.

## Manipulators

The LPFOAs & SPFOAs in the Orion beamlines both use a class of mechanism called parallel manipulators. These manipulators allow accurate positioning of the optic assemblies. In parallel manipulators each of the actuators is mounted to the same base, unlike a serial mechanism where each actuator is mounted on the output end of the previous actuator. Figure 2 shows a comparison of serial and parallel manipulators

One type of parallel manipulator is known as a hexapod, shown in Figure 2b, which consists of a fixed base platform onto which 6 independent extendable legs are attached via ball joints. The other ends of all 6 legs are mounted on the payload platform, shown in green in Figure 2b, also via ball joints. This triangulated mechanism produces an extremely stiff structure.

In order to manipulate the output platform, each of the legs must be moved to a new calculated length. Whilst requiring all the actuators to move to perform a simple unidirectional movement may not seem like an ideal situation, any error in an individual leg plays a smaller part in the resulting final position. This results in a total error in position which is less than the error in any one single leg.

## Short Pulse Final Optics Assembly (SPFOA)

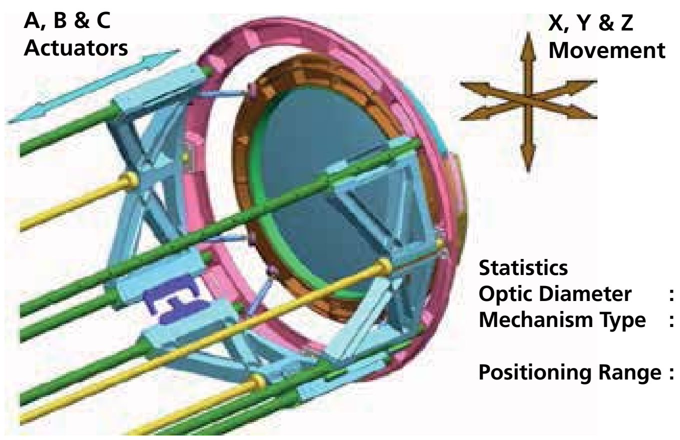
The SPFOA is the last optical component in the short pulse laser chain. The mechanics of the SPFOA is a 6 degree of freedom hexapod. The mechanism consists of a fixed base platform onto which 6 independent extendable legs are attached via ball joints in a triangulated arrangement. The other ends of all 6 legs are mounted in a cradle also via ball joints. The parabolic mirror is then mounted into and supported by the cradle. Figure 3 is a model of the SPFOA which shows the hexapod base in blue; the payload is the mounting cradle for the mirror and is green in the model.

**FIGURE 3**

**Statistics**
**Optic Diameter : 720 mm**
**Optic Weight : 250 kg**
**Mechanism Type : 6 axis parallel manipulator**
**Mechanism Weight : 50 kg**
**Positioning Range : 35 mm sphere at Target Chamber Center**
**Angular Range : 0.15° around twice the focal length**
**Positioning Resolution : < 0.1 μm**

Model of the Short Pulse Final Optic Assembly with statistics.

**FIGURE 4**



**Statistics**
**Optic Diameter : 350 mm**
**Mechanism Type : 3 axis parallel manipulator**
**Positioning Range : 35 mm sphere at Target Chamber centre**
**Positioning Resolution : < 0.1 μm**
**Retraction Travel : 1250 mm**

Model of manipulator used for the Long Pulse Final Optic Assembly.

## Long Pulse Final Optics Assembly (LPFOA)

The LPFOA comprises of the last few optical components in the laser chain (chamber window, focus lens, debris shield and phase plate) mounted in a parallel positioning mechanism which enables the incoming laser beam to be focused down onto the target. A retraction mechanism is provided to enable easy access to the debris shield for operational expediency.

The LPFOA utilises a special parallel manipulator mechanism. There are only 3 actuators which are connected to the output frame via 6 fixed length bars which are oriented to be parallel to each other. This parallel joint constrains the rotational degrees of freedom so that the lens can only be translated linearly and cannot rotate. Figure 4 is a model of the manipulator used in the LPFOA. In addition to the 3 actuators providing the X,Y & Z translational movement, all 3 of the sliders can be moved simultaneously to retract the lens to larger distances. The primary use for this is to position the lens and debris shield assembly outside of the target chamber wall to enable the debris shields to be changed.

## Target Positioning System (TPS)

The TPS is the device used to position and orient the target into the required position within the target chamber. The TPS utilises a traditional serial stacked slide system which uses piezo actuators for the X, Y and rotary stage followed by a counterbalanced piezo Z stage. A model of the serial stacked slide system is shown in Figure 2a. Figure 5 is an image of the TPS used in the Orion target system.

**FIGURE 5**

**Statistics**
**Mechanism Type : Serial Stacked Slides**
**Linear Travel X/Y : 100 mm**
**Linear Travel Z : 115 mm**
**Angular Travel : 320°**
**Resolution : 0.01 ° and 0.3 μm**

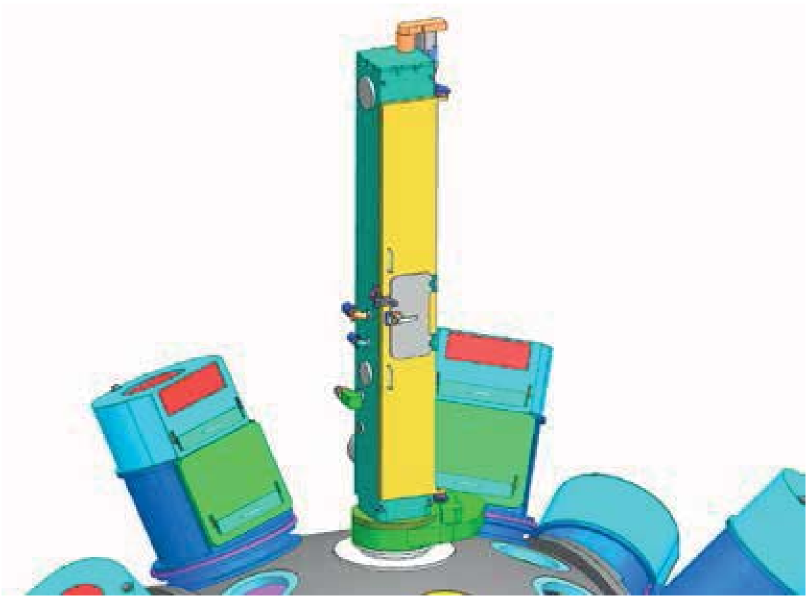
Image of the Orion Target Positioning System and statistics.

## Target Inserter (TI)

The target inserter is used to transfer the target from outside the chamber and place it on the target positioner while the target chamber is at vacuum. The target inserter utilises a telescopic boom mechanism so that the total travel of the target is significantly longer than the volume it occupies. This results in the fully retracted position being half way up the inserter body, which allows the target holder to be replaced at an ergonomic height. Figure 6 is an enlargement of the Orion target system highlighting the position of the TI

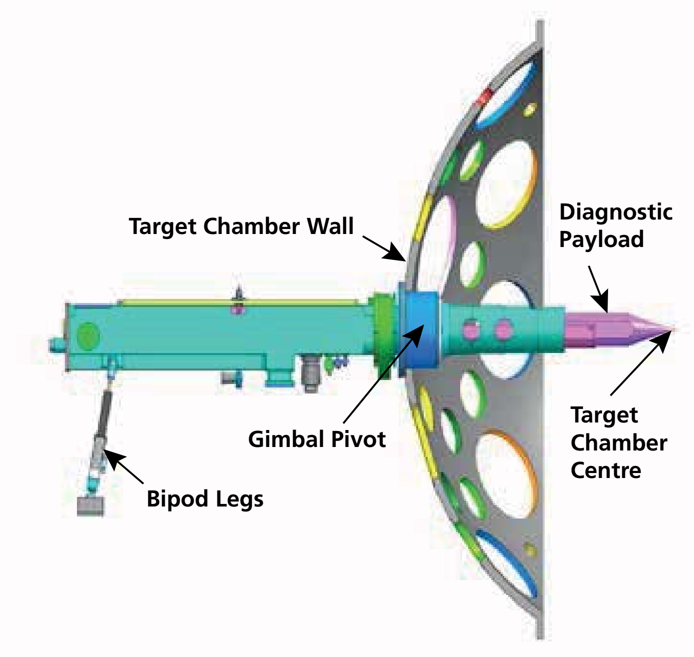
**FIGURE 6**

**Statistics**
**Mechanism Type : Telescopic boom**
**Total Travel : 3450 mm**
**Retracted Size : 2500 mm**
**Vacuum : Independently pumped from the Target Chamber**



**Model showing position of the Target Inserter in the Orion Target System and statistics.**

**FIGURE 7**



**Statistics**
**Mechanism Type : Linear Slide & Bipod Legs**
**Total Travel (In & Out) : 2370 mm**
**Total Travel (Up/Down, Left/Right) : 30 mm**
**Positional Resolution (Z) : < 0.5 µm**
**Positional Resolution (Up/Down, Left/Right) : <0.2 µm**
**Isolation : Independently pumped from the Target Chamber**

**Cross sectional model of a Ten Inch Manipulator.**

## Ten Inch Manipulator (TIM)

The TIM is used to provide a load-lock and insertion mechanism for diagnostic payloads on Orion. There are six TIMs located around the Target Chamber; The TIM utilises a linear slide system for insertion and removal of the diagnostic and bipod legs at the rear to change the orientation. The TIM body pivots around a gimbal just inside the target chamber wall. Figure 7 is a cross sectional view of a TIM. Figure 8 is a model of the TIMs interacting with the target chamber.

## Target Viewer and Illuminator System (TVS)

The Target Viewing system provides two orthogonal views of the target with back illumination with both red and blue light selectable by the user. Each of the viewers also provides two fields of view, a wide view covering a 30 mm circle and a narrow view covering a 5 mm diameter circle.

**FIGURE 8**

**Ten Inch Manipulator Locations on the Orion target chamber.**

# Orion Control System

**The Orion laser facility has been designed to be capable of firing in excess of six shots onto shot specific targets in one day. It was acknowledged at an early stage in the project that a sophisticated control system would be required to allow this capability to be achieved. The control system provides remote control and configuration for thousands of components that include multi-axis mirrors, diagnostic manipulators, hexapods, oscilloscopes, cameras and other diagnostics. The data relating to a shot's setup and the diagnostics data acquired at shot time are required to be stored and made available to scientists for analysis.**

## Design

Due to the complexity that could be foreseen in the system the control system was split into distinct sub-systems; these sub-systems were required to abide by interface standards to allow easier integration and commissioning.

These sub-systems include:

- Integrated Control System (ICS).
- Target Data Acquisition System (TDAS).
- Laser Alignment and Diagnostics.
- Target Alignment and Diagnostics.
- Pulsed Power – Capable of delivering 10 MJ in 600 $\mu$s.
- Vacuum System.
- Timing System – Capable of sub 10 ps jitter.
- Safety Interlock System (SIS).
- Building Management System (BMS).

To allow detailed design and testing to take place a development and prototyping facility was provided; this was named Osiris. This facility allowed in-house design engineers to prototype and test systems to select and prove suitable solutions. Having a facility to prototype and test as early as possible was an essential requirement in order to deliver a working control system on time. A room within the Orion building has been allocated to provide the same on-going design, prototype and test capability for the life of the Orion Facility.

## IT Infrastructure

A control system requires communications between its components. This communication has been facilitated by the installation of an IT Network based on a 10 gigabit fibre-optic backbone that is routed through 20 km of multi-mode fibre-optic to the order of 150 extreme network switches.

These switches are distributed throughout the facility in 2 metre high control system enclosures. Each enclosure allows local equipment to be mounted near its required location and have Ethernet connections onto the network available. This high speed network allows for fast transmission of large amounts of data.

The network architecture encompasses three separate Active Directory Domains. These domains are purposefully segregated from each other and hence each has its own set of servers to support the functions required on each domain.

The Integrated Control System (ICS) domain is predominately used to guide the laser to the target chamber. The Unclassified Target Data Acquisition System (UTDAS) domain is used for the final guidance of the laser onto target and to record data gathered when the shot is fired. Finally the Classified Target Data Acquisition System (CTDAS) domain is a mirror copy of the UTDAS domain but is only used when there is a requirement to fire classified shots.

Each of the three domains has a database server. These servers store all required data related to the setup of the laser and diagnostics prior to a shot and all data acquired during the shot. The database servers provide 30 terabytes of storage across three databases.

The hardware systems that utilise the provided domains range from oscilloscopes, motion controllers, enclosure mounted computers and specialised diagnostic systems.

## Control System User Interfaces

The design of the Orion laser requires that, during a shot, the laser hall, target hall and compressor hall are not occupied. This necessitates the ability to remotely configure and control devices. This is achieved by providing operator workstations that run a Supervisory Control And Data Acquisition (SCADA) application.

The ICS and the TDAS are high level systems that are operated via specific rooms. The ICS is operated via the Control Room and TDAS from either a classified or an unclassified operations room.

Workstations within the Control Room are dedicated to specific operations that are required to configure and control the laser. The status of systems required for the configured shot is summarised and displayed. When all configured systems are in the required state the Shot Director can transition through the states to initiate the charging of the capacitor banks and when these are charged they can fire a shot.

Due to hazards present in areas of Orion during operations a system is required to ensure the safety of personnel. The Safety Interlock System (SIS) is designed to protect personnel from hazards which comprise of high voltages, intense laser light, and ionising radiation.

The SIS incorporates a series of mechanical and electrical safety switches that restrict access to laser controlled areas. A custom designed key exchange is provided to prevent the presence of high voltage until necessary.

The SIS also provides a series of safety switches to allow safe shutdown of operations. The SIS is a stand alone system that does not rely on any other systems and is Safety Integrity Level 2 (SIL 2) rated.

An important function required is the ability to remotely and locally control motion controllable devices. These include multi-axis mirrors, binary insertion devices, linear stages and diagnostic manipulators, in total in excess of 1200 separate controllable axes.

To provide control signals and power to all motion controlled devices, over 35 km of cabling has been installed in specifically designed containment. These interfaces can be used by operators to view the status and control the position of motion controllable devices. The status information for multi-axis mirrors and binary insertion devices such as cross wires is displayed to operators.

Once the laser beams have been aligned in to the target chamber then alignment onto the target is also required. Each beam used for the shot needs to point at a specific location on the target. The alignment and focus of the laser beams on to target is achieved by a combination of movements of the final optics and the target itself.

Cameras are used to observe the relative positions of focal spot and target using alignment beams. These interfaces are provided on the TDAS.

The Equipment Protection System displays an overview of the positional status of this equipment that is located in and attached to the target chamber. This is used to check for correct and safe equipment positions before any equipment movement commands are issued.

> "The SIS is a stand alone system that does not rely on any other systems and is Safety Integrity Level 2 (SIL 2) rated."

### BOX 1

Given the nature of the work taking place at Orion, a safety interlock system (SIS) is required to protect personnel from various hazards in the building, including high voltages, intense laser light and ionising radiation.

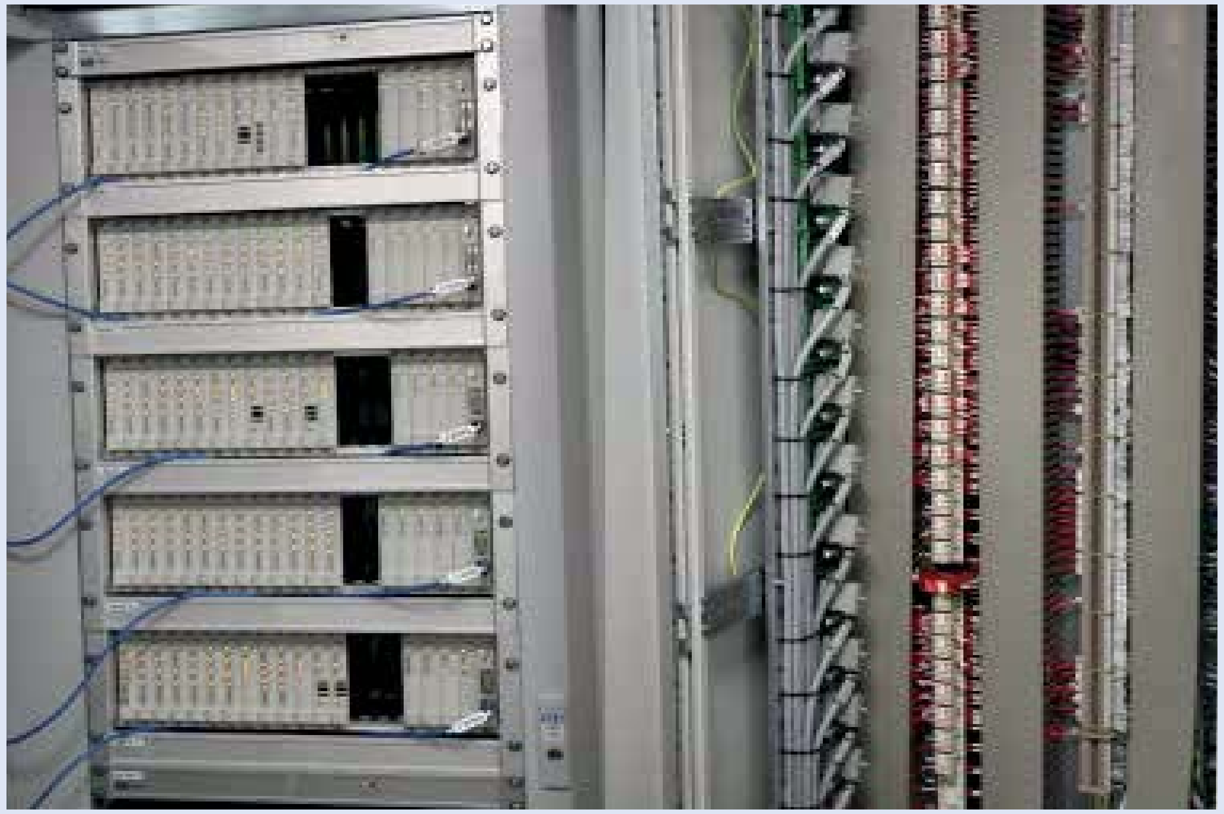
The SIS is an independent system that provides permissive signals during safe operations, to allow the use of lasers, pulsed power and a series of shutter systems.

At the heart of the SIS is the logic solver, a complex, custom built interface that is continually monitoring the state of all the field device equipment, including airlocks, emergency stops and laser key switches. The logic solver feeds a marshalling panel which consists of a series of safety relays and switches, all providing a reliable conduit to each laser controlled area (LCA).

Incorporating a custom built key exchange system; the SIS restricts access to LCAs to fully trained personnel and prevents the presence of high voltage until absolutely necessary.

During laser shot time this key exchange system provides the ability to search each LCA in turn, ensuring that all areas are vacated. Once the areas have been searched the system prevents access to high hazard areas until the laser shot has been completed.

Being rated to safety integrated level 2 the SIS provides a highly reliable protection system, providing confidence to scientists as they embark on exciting new experiments within the field of plasma physics.



**Typical Laser Controlled Area conduit**

# Buildings

**The lasers and process equipment contained within Orion require a clean, stable and tightly controlled environment in order to be able to meet the high performance demands. This can only be achieved by a building and plant configuration that is very different to that normally found in typical buildings.**

Isolation from the external environment is vital to support accurate laser alignment. Vibrations and movements caused by wind or passing traffic are transmitted unnoticed into most building structures but are not acceptable to the Orion lasers. The outer shell of the Orion building is physically separated from central slabs which support the lasers – so any disturbance to the building shell has no impact on the lasers. The concrete piles under the building are over 30 m deep to ensure the building remains stable in all environmental conditions.

Small changes in atmospheric temperature or humidity, or tiny amounts of airborne dust can also affect the propagation of laser light. The building ventilation system maintains the temperatures in the main laser areas steady to better than ± 0.2 °C (exceeding the ± 0.5 °C specification), whilst keeping humidity to better than ± 5%. There are 339 fan filter units to pass the air through high efficiency particulate air (HEPA) filters, continually cleaning the air. Together with clean room clothing and procedural controls, this ensures that the air in the Orion clean rooms typically contains as little as one thousandth of the dust levels of typical office air.

To ensure the level of environmental control, monitor the multitude of services supporting the building processes and alert operators and site control to any fault as soon as it occurs, the building plant is connected to a comprehensive building management system (BMS).

The BMS monitors the building and plant conditions using over 550 sensors, simultaneously running over 350 separate programmes to automatically control and adjust plant operating parameters to ensure that all the equipment performs within specification. The facility engineering team can log the sensor inputs, monitor the plant and manually override settings from a user-friendly graphics interface on the main BMS computer.

Not only does the laser process place stringent requirements on the building performance, it also introduces harsh environments that could adversely affect people or equipment. The target hall has 1.5 m thick concrete walls with a comprehensive Electromagnetic Pulse (EMP) shield to ensure people are not exposed to dangerous levels of EMP or radiation.

The EMP and radiation would also damage modern digital electronic systems that have to remain within the target hall during a shot. A number of technical solutions have been required, such as comprehensive shielding and remote sensors.

The Orion building was designed to meet modern environmental standards in support of the company values of 'Safe, Secure and Clean'. It was awarded an 'Excellent' rating by BREEAM (Building Research Establishment Environmental Assessment Method) after a detailed assessment of the building's environmental performance.

Despite the complexity of the challenges involved, the building, plant and support services have performed successfully throughout the commissioning campaign, to enable AWE to meet the first full power laser shots without causing any delay to the programme; a proud record that has enabled the Orion lasers to concentrate on supporting the United Kingdom's capability.

# Inertial Confinement Fusion

## and Prospects for Power Production

**The Orion laser facility's primary use is for the underwriting of the safety and performance of the United Kingdom's nuclear deterrent. It is also available for access for academic programmes at 15% of the available time and as such provides a facility for research into the field of plasma physics. One such area that Orion is thus able to support is research into laser driven Inertial Fusion Energy (IFE).**

The principle of fusion is simple, although its realization on an industrial scale suitable for commercial energy production is technologically demanding. The underlying physics involves using extremely powerful lasers to heat a mixture of two hydrogen isotopes, deuterium and tritium, to extreme temperature whereupon the constituent nuclei fuse to form an alpha particle (helium ion) and a neutron according to the reaction shown graphically in Figure 1.

Following each fusion reaction, the helium ion and the neutron carry excess energy of approximately 17.6 MeV, millions of times greater than is liberated in a typical chemical reaction. Whilst there are several potential fusion reactions, the deuterium and tritium (D-T) reaction has the highest cross section and is thus the most favourable for energy production.

The largest laser in the world, the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL) will attempt to demonstrate the principles of laser driven fusion by imploding small D-T capsules. Rather than attempt to compress and heat all the fuel in a capsule at once, the aim is to use the laser to heat a small volume of the D-T fuel, a hotspot, so that fusion reactions occur. If it can be ensured that the fusion energy released is deposited within the hotspot itself, the temperature will be raised further so that the fusion reactions proceed at a higher rate and heat the surrounding cold D-T fuel to produce a propagating burn wave.

The requirement for self heating of the hotspot region gives rise to a fundamental condition for efficient burning of the fuel. The 14 MeV neutron is a small, highly energetic neutrally charged particle that typically escapes from the central hotspot of the fuel without depositing significant energy. The alpha particle is larger, less energetic, positively charged and much more likely to become trapped within the hotspot.

The likelihood of trapping the alpha particle depends simply on the amount of material it must penetrate before leaving the hotspot region. This can be expressed as an "areal" or "column" density, ρ.r, where ρ is the fuel density and r the radius of the fuel in the hotspot. For 3.5 MeV alpha particles in a D-T mixture, the trapping condition is that ρ.r ~ 0.3 $\text{gcm}^{-2}$.

The energy required to heat the hotspot to the temperature at which fusion reactions occur, E, is given by the product of the hotspot mass and the temperature $T_i$ and the specific heat $C_v$:

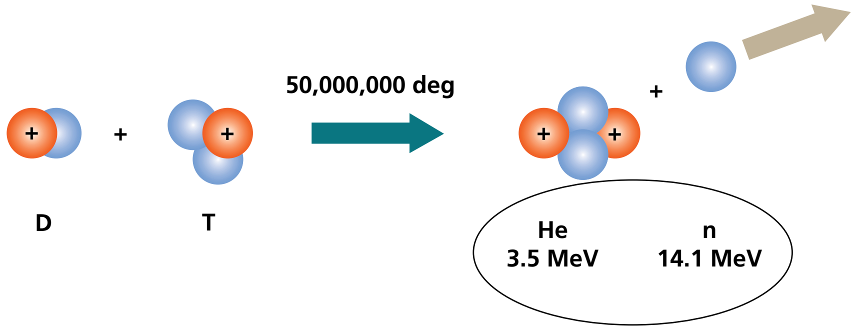
$$E = [(4/3\ \pi.T_i.\ C_v) \times (\rho.r)^3]\ /\ \rho^2$$

But since ρ.r is fixed at 0.3 $\text{g.cm}^{-2}$ by the alpha trapping condition, the energy can be expressed by

$$E = k\ /\ \rho^2$$

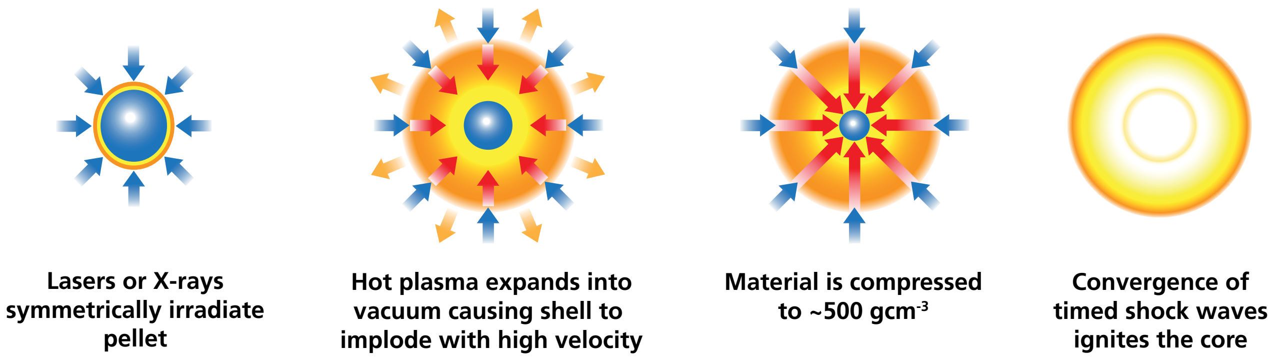
Where k is a constant. By compressing the fuel to high density, the energy needed from the laser is reduced by the compression factor squared. It is

**FIGURE 1**



The D-T fusion reaction at the heart of laser energy.

**FIGURE 2**



Overview of compression and heating process in laser fusion.

this inverse square dependence of the ignition energy with density that enables inertial fusion to be brought within the reach of currently available laser technology.

In laser fusion the laser must perform two distinct functions. Firstly the D-T fuel is compressed to the density required to trap the fusion alpha particles, secondly the hotspot is heated to fusion temperature, producing a burn wave which propagates through the entire fuel mass.

Great care must be taken during the compression phase as premature heating would cause the fuel pressure to increase, requiring increased energy from the laser. The solution is to shape the laser pulse so that the compression occurs adiabatically, in the absence of shocks, to keep the fuel temperature low.

Once the fuel capsule is fully compressed, the laser power is increased rapidly to launch a number of shock waves into the fuel which coalesce at the centre to produce a hotspot and raise the temperature to the ignition point. The process of compression and heating by the laser is shown schematically in Figure 2.

The scientific proof of principle of the basis of inertial fusion was demonstrated in a series of underground nuclear tests in the 1980's. Since that time, a vigorous experimental and computational programme has been undertaken to demonstrate laser-driven ignition and burn of a D-T fuel capsule.

In 2010, the 192 beam, 1.8 MJ NIF was commissioned at LLNL in California. This facility has been used by the National Ignition Campaign to conduct experiments that have made rapid progress toward achieving First Ignition. A demonstration of net energy gain is anticipated around 2014.

In the UK, scientists also have access to unique, large scale, world leading laser facilities; VULCAN at Rutherford Appleton Laboratory and Orion at AWE, shown in Figure 3. These facilities are not large enough to reach the conditions for fusion gain, but they are ideally suited to experiments designed to validate the numerical simulations on which inertial fusion depends and to investigate the underlying physics of the key processes.

Orion is particularly well suited to measuring the opacity and equations of state of materials at high density and temperature. Such measurements will help to improve the fidelity of the numerical simulations used for First Ignition. Following First Ignition, it will be necessary to tune the configuration of the NIF fuel capsules and the laser parameters to optimize the energy gain of the system, to improve the robustness of ignition and to explore the sensitivity of the gain to imperfections. This will require a large number of experimental laser shots. With its high shot rate, Orion will be able to make an important contribution to this optimization process.

**FIGURE 3**

Laser bay of AWE's new Orion facility.

## Challenges Ahead

The fundamental assumption supporting the case for laser driven fusion is that First Ignition will be demonstrated at NIF. Beyond First Ignition and physics optimization, substantial technical challenges remain in three main areas.

## Laser Driver

A step change in laser technology is required to meet the driver specification. This is now possible through development of high-efficiency laser diodes. Diode Pumped Solid State Laser (DPSSL) technology offers high average power high repetition rate operation at high efficiency.

At the Central Laser Facility at Rutherford Appleton Laboratory, prototype DPSSL lasers are already operating at 10% overall efficiency and a 100 J / 10 Hz prototype is under construction. The scaling of such systems to the 10 kJ level seems entirely feasible.

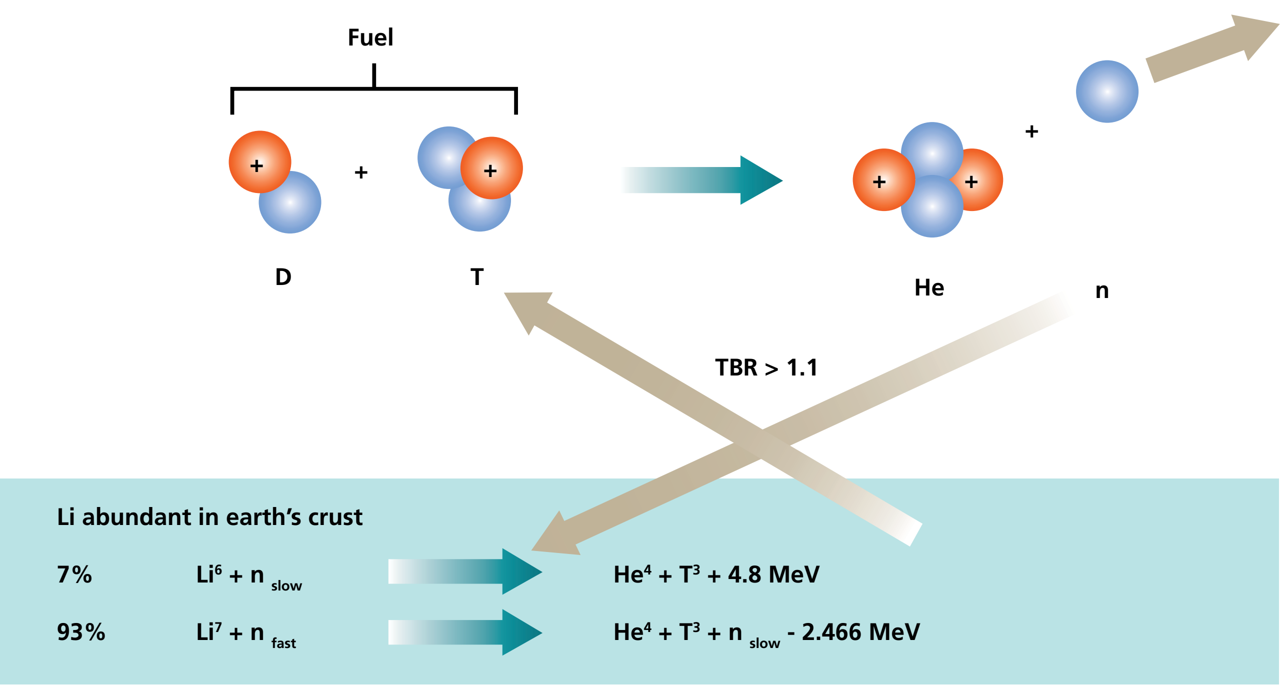
## Energy Capture and Fuel Cycle

Deuterium is an abundant constituent of seawater and can be extracted by chemical means. Tritium, however, is radioactive with a half life of 12.3 years, not available naturally in sufficient quantities and must be generated within the fusion fuel cycle itself.

Lithium is abundant in the earth's crust and is the ideal material both to capture the energy of the fusion products and as a source of tritium, produced in reactions with the fusion neutrons as shown in Figure 4. The lithium will be held in a "blanket" surrounding the fusion reaction chamber.

There are two isotopes of lithium that will be used in the blanket, lithium 6 and lithium 7 as shown in Figure 4. The neutron reaction with lithium 6 is exothermic, adding more energy to the system while the lithium 7 reaction is endothermic. Both reactions form tritium and in the lithium 7 case, the neutron is "preserved" so that it can take part in a subsequent lithium 6 reaction. Addition of lithium 7 therefore enables excess tritium to be produced to replace losses and also to generate a surplus as would be required to

**FIGURE 4**



**Neutron capture and tritium generation in lithium.**

fuel the "start-up" of new fusion power plants.

To extract the fusion energy from the blanket, the lithium will be circulated through heat exchangers. Engineering expertise and capability associated with liquid sodium cooling of fission power plants is readily transferrable to lithium in fusion energy plants. Extraction of tritium from the liquid lithium and its recovery from the waste stream of any un-burnt fuel capsules remains to be demonstrated.

## Fuel Capsule Production

Possibly the greatest challenge facing energy production from laser driven fusion is the mass production of fuel capsules to the required quality and cost. For IFE to be a practical energy source a power plant will require approximately one million fuel pellet targets per day. This requires a step change in manufacturing techniques to increase production rates and reduce cost.

## Summary

Laser driven fusion energy is based on the conversion of isotopes of hydrogen into helium through the process of fusion, using lasers as a driver. This technology could provide an energy solution on the 2040 – 2050 timescale with the potential to supply a significant proportion of world energy needs beyond 2050.

First Ignition at NIF will pave the way for a programme of technology development prior to construction of a prototype Laser Energy plant to demonstrate power production on a commercially attractive basis.

The UK has the knowledge, skills and capabilities to make a substantial contribution to a programme to realise Laser Energy on a timescale relevant to meeting world energy needs.

As one of the premier national laboratories, and although it does not currently have a remit to study fusion energy itself, AWE represents a major source of this capability, with its large scale computing resources, the Orion laser facility and a highly skilled and experienced team of scientists, technologists and engineers.

**BOX 1**

## The HiPER Project

High Power Laser Energy Research (HiPER) is a pan-European ESFRI (European Strategy Forum on Research Infrastructures) project that seeks to demonstrate the production of secure, sustainable, safe and affordable energy with low environmental impact based on fusion driven by lasers and on a timescale relevant to meeting the challenges of the energy gap on the 2050 timescale.

Coordinated by the Science Technologies Facilities Council (STFC) at the Rutherford Appleton Laboratory, HiPER has created an exceptional opportunity for Europe to partner with the US and other international partners in the approach to First Ignition and to develop an international approach to Laser Energy.

While not a formal partner of the HiPER Preparatory Phase Project, AWE is making valuable contributions to the work, particularly in numerical modelling of the physics, target design and target fabrication. AWE is also contributing to Livermore's Laser Inertial Fusion Engine (LIFE) project and is a signatory to a MoU (Memorandum of Understanding) between Livermore, STFC and AWE, to collaborate on the realization of Laser Energy. The MoU enables the free exchange of data and information and serves as a framework for joint working. AWE does not currently have a remit to work on IFE, but by working at the low level described it is able to access knowledge and peer review information valuable to its core programmes. With appropriate funding AWE could expand its IFE work with the UK and internationally.

Studies of the economic viability of laser driven fusion energy have been conducted by both the LIFE and HiPER projects and the results are in broad agreement. The major conclusions are that a future plant must run at a repetition rate of at least 10 Hz, that a fusion energy gain in excess of 60 is required and that the wall plug efficiency , laser energy out divided by the electrical energy in, of the laser driver must exceed 10%.

The HiPER strategy is to exploit the independence of the technologies by demonstrating prototypes in each of the key areas. The HiPER schedule is based on the assumption that First Ignition at NIF will be achieved by the end of 2014, followed by a process of gain optimisation and ignition robustness studies until the mid 2020s using both NIF and LMJ (Laser MegaJoule, in France) facilities.

# AWE's Outreach

# Major Events and Collaborative Activities

**In this section, we cover a number of high-profile events and conferences in which AWE has been involved. They represent a wide range of disciplines and areas of expertise and also put AWE's relationship with key stakeholders into context.**

## UK PONI

Some 150 scholars and established experts gathered at the second annual AWE co-sponsored UK Project On Nuclear Issues (UK PONI) Conference, held on 10 May 2012 on board HMS President. The event, opened by Lord Hutton of Furness the Chairman of the Nuclear Industries Association, centred on 'Nuclear stability: from the Cuban Crisis to the Energy Crisis', themed to coincide with the 50th anniversary of the Cuban Missile Crisis.

Lord Hutton spoke candidly about how PONI has created an environment where lessons learned from the past 50 years can be conveyed to the next generation of nuclear decision and policy makers through innovative thinking.

UK PONI is a cross-generational forum allowing nuclear scholars to engage with experts on a wide variety of contemporary issues. As part of the US PONI founded in 2003, UK PONI aims to promote the study on nuclear issues with a European focus.

Topics presented focussed on crises and stability, nuclear energy, non-proliferation, threat to stability, and geopolitics and regimes. AWE looks forward to the next series of PONI conferences.

## Nitrocellulose Symposium

On 17-18 April 2012, AWE jointly sponsored the 5th International Nitrocellulose Symposium with Nitrochemie and Armasuisse in Spiez, Switzerland.

This was the latest in a series of nitrocellulose workshops that AWE has supported since 2001 which have grown steadily from the beginnings of a small, focussed workshop on nitrocellulose molecular mass determination to a fully fledged international conference.

The forum attracted over 90 delegates, representing 18 nations from four continents (Europe, Asia, North America and Africa).

More than 30 scientific papers were presented which specifically addressed the symposium themes of characterisation, ageing and manufacturing of military and industrial nitrocellulose; this complex, naturally-derived material continues to be widely used in a variety of applications including inks, coatings and energetic materials. Nitrocellulose is a key component of our warhead programme.

The 6th Nitrocellulose Symposium will be hosted in 2014 by TNO, an independent research organisation based in the Netherlands.

## Insensitive Munitions and Energetic Materials Technology Symposium

AWE sponsored the 2012 Insensitive Munitions and Energetic Materials Technology Symposium held in May in Las Vegas, USA. The event attracted 250 attendees from around the world.

AWE supported the networking event through their membership of the Insensitive Munitions Energetic Materials Group leading to future collaborative opportunities for AWE. AWE also authored two papers: a formulation with a novel high energy and insensitive plasticiser and the development of improved testing regime.

## Materials Science Exhibition

On 30-31 May 2012, AWE hosted the Materials Science Exhibition at Aldermaston. The exhibition and presentations showcased work across the company relating to materials science achievements and delivery, all of which are aligned to AWE's technical programme.

Topics included materials research and development, detection and analysis, processing and testing, trials and diagnostics, component ageing and compatibility, forensics, treaty verification, modelling, extreme environment studies, and operational activities.

Over 100 representatives from MOD, UK academia, Dstl, NPL, NNL, the Home Office, the Department of Energy and Climate Change, Engineering and Physical Sciences Research Council and Science Engineering Technology Advisory Committee panel members attended the event. Visitors and staff commented on how impressed they were with the breadth and depth of AWE's materials science research.

## Plutonium Futures - The Science

Some 230 scientists from 18 countries, including over 20 materials scientists and chemists from AWE, gathered at the Plutonium Futures – The Science conference held at the University of Cambridge on 15-20 July 2012.

Hosted by AWE and chaired jointly by AWE, the CEA in France, the JRC-ITU in Germany and the UK NNL, the international forum presented and discussed current research on the physics, chemistry and materials science of plutonium and other actinide elements.

The event was the seventh in a series of international conferences originating from the US National Laboratories. Issues relating to condensed matter physics, materials science, detection and analysis, the environment and the nuclear fuel cycle involving plutonium were discussed.

## Enhanced Detection of Special Nuclear Material

AWE scientists were among 100 international experts in the nuclear detection field who gathered at the second Symposium on Enhanced Detection of Special Nuclear Material, held on 1-2 November 2012, at the magnificent Lancaster House, London.

The symposium, convened under the auspices of the Global Initiative to Combat Nuclear Terrorism (GICNT), was co-sponsored by the Foreign & Commonwealth Office (FCO), AWE, the Defense Threat Reduction Agency, and MOD. GICNT's mission is to strengthen global capacity to prevent, detect and respond to nuclear terrorism by conducting multilateral activities that support the plans, policies, procedures and interoperability of partner nations. GICNT is coordinated by the US and Russian Federation.

The forum covered a range of important issues that relate to improving techniques to detect nuclear material in order to prevent illicit trafficking.
It was opened by the FCO Minister for Counter-proliferation and Counter-terrorism, Alistair Burt MP.

The discussion and debate included recent progress in nuclear detection and research – with the overarching aim being how to keep our world safe and secure.

## Defence Science and Technology Showcase

AWE participated in the 'Defence for today and tomorrow' science and technology showcase led by MOD and Dstl, held on 12 December 2012 in the Memorial Hall at MOD Main Building in London. The one-day event invited a number of key defence organisations with the overarching aim of demonstrating practices and approaches to working together in delivering science, engineering and technology for the UK.

A number of leaders from industry and academia as well as A-level science students attended the exhibition during which they were given demonstrations of leading-edge science and technology. AWE showcased its capability and expertise with displays of the Orion laser; a high energy density physics experimental facility, its support to national nuclear security and Continuous At Sea Deterrence, and collaborative engagements with universities – including exhibits comprising components manufactured using rapid prototyping.

## Energetic Materials

Over 40 leading international experts from 11 countries gathered at the AWE hosted 8th Heat Flow Calorimetry Symposium on Energetic Materials, held on 29-31 October 2012 at Wokefield Park, Reading. The forum included presentations on kinetics and data evaluation, calibration issues, method development and application to nitrocellulose propellants, and some high explosives.

## Fusion Energy

In association with the Institute of Physics (IOP) AWE Chief Scientist, Professor Peter Roberts OBE and Director of the Culham Centre for Fusion Energy, Professor Steve Cowley gave a joint presentation on fusion energy and the challenges ahead to the IOP Plasma Group on 4 April 2012 at St Hugh's College, Oxford.

The efforts to achieve laser fusion were discussed along with a summary on magnetically confined fusion energy which has been pioneered at Culham in Oxfordshire.

## High Value Manufacturing

Head of Manufacturing and Interim CEO of the High Value Manufacturing (HVM) Catapult at the Technology Strategy Board (TSB), Will Barton, visited AWE in May 2012 to explain the Government's HVM strategy. The TSB is a national body set up to invest in innovation working across business, government and universities.

A major initiative is the Catapult concept which will create centres of excellence; the first to be created was the HVM Catapult comprising seven individual centres.

**Alistair Burt MP addressing delegates at the Symposium on Enhanced Detection**

# Discovery 24

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